Induction Coilgun for EM Mortar *

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Abstract

The Defense Advanced Research Projects Agency is investigating electromagnetic (EM) guns for the next generation combat vehicle providing improved performance and survivability without the use of propellant. The two-year program was initiated in 2005 to design a coilgun and a railgun to launch an existing mortar round with an EM armature in laboratory conditions at speeds to increase range beyond current capabilities.

This paper describes a laboratory coilgun system whose requirements are based on the Future Combat System Mortar Vehicle for indirect fire applications. Minimal adaptation has been necessary to existing mortar rounds with the armature and support structure necessary for EM coilgun launch. High magnetic field coils have been designed and tested at stress levels anticipated during launch. Recoil from the barrel of stacked coils will be managed by a conventional gun mount integrated to a catcher through a structural frame. Capacitor bank modules currently in fabrication and test utilize 1980's technology capacitors, but new ideas in commercial components for switches, resistors and bus-work are investigated to lower cost. The firing system, which includes a projectile-sensing 94 GHz radar triggers the capacitor banks for optimal performance and precise muzzle velocity control, is also described.

I. DARPA EM Mortar Program

The Defense Advanced Research Projects Agency is investigating electromagnetic (EM) guns for the next generation combat vehicle providing greater range, accuracy, and survivability without the use of propellant. Electromagnetic guns can provide high-fidelity controlled muzzle velocity, which removes the largest source of error in target accuracy. A two-year program was initiated in 2005 to design a coilgun at Sandia National Laboratories and a railgun at the Institute for Advanced Technology at the University of Texas to launch an existing mortar round with an EM gun armature in laboratory conditions at speeds to increase range beyond current capabilities.

The goals of the laboratory demonstrations include several aspects of performance. Minimally-modified 120 mm, M934 rounds will be launched at conventional-propellant mortar speeds (up to 320 m/s), and also at the EM Mortar objective of 420 m/s. The increased speed will result in a 30% range increase to 9 km. An additional goal is to demonstrate the reproducibility of muzzle speed control with a standard deviation of less than 1% at each of six test speeds. Gun lifetime will be assessed with the goal of 100 shots during the test campaign.

II. Coilgun Components

The components of the laboratory induction coilgun assembly discussed in this paper are shown in Fig. 1. The coilgun consists of solenoidal coils constrained in a gun barrel structure connected to a gun mount with recoil mechanisms. This mount is similar to what will be needed for future applications and capable of firing at variable elevation angles. The coils are energized sequentially from individual capacitor banks (not shown) controlled by a firing system that senses the projectile position and velocity as shown in Fig. 2 for precise muzzle velocity. When energized by the discharge current of the capacitor bank, the coil's magnetic field induces opposing currents in the conducting armature ring on the projectile generating thrust from the Lorentz force.

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14. ABSTRACT
The Defense Advanced Research Projects Agency is investigating electromagnetic (EM) guns for the next generation combat vehicle providing improved performance and survivability without the use of propellant. The two-year program was initiated in 2005 to design a coilgun and a railgun to launch an existing mortar round with an EM armature in laboratory conditions at speeds to increase range beyond current capabilities. This paper describes a laboratory coilgun system whose requirements are based on the Future Combat System Mortar Vehicle for indirect fire applications. Minimal adaptation has been necessary to existing mortar rounds with the armature and support structure necessary for EM coilgun launch. High magnetic field coils have been designed and tested at stress levels anticipated during launch. Recoil from the barrel of stacked coils will be managed by a conventional gun mount integrated to a catcher through a structural frame. Capacitor bank modules currently in fabrication and test utilize 1980s technology capacitors, but new ideas in commercial components for switches, resistors and bus-work are investigated to lower cost. The firing system, which includes a projectile-sensing 94 GHz radar triggers the capacitor banks for optimal performance and precise muzzle velocity control, is also described.

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The laboratory test range includes diagnostics to determine projectile integrity in free-flight before impacting a steel catch box. The 3.7 m long barrel is longer than necessary for future applications as this laboratory version contains a projectile drift and diagnostic section and barrel elements intentionally placed external to the gun mount.

Figure 1. Coilgun mounted in an FCS-type gun mount with catch-box for laboratory tests.

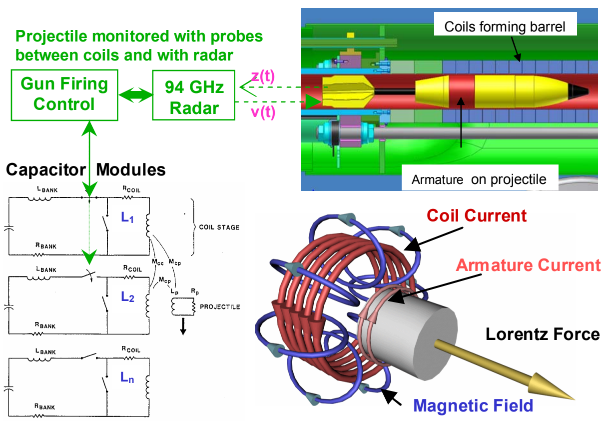

Figure 2. System components of induction coilgun.

III. Projectile

The XM934 EM Mortar coilgun round shown in Fig. 3 was developed by the Future Munitions Branch, Armament Research, Development and Engineering Center (ARDEC) at Picatinny Arsenal and Sandia. The 18 kg integrated launch package contains a cylindrical armature and support structure in a modified screw-on tail kit that flies to target with the unmodified warhead payload. Wind tunnel testing of models provided the basis for changes to the boattail, tailboom and fins to accommodate the assembly center-of-gravity and operation at transonic speeds. Range greater than 9 km is anticipated as designed, with additional range possible with adjustment to the warhead nose.

Figure 3. XM934 EM coilgun projectiles and tail kits.

IV. Tracking Radar and Firing System

Precision fire-control of the barrel coils is achieved with an active controller with realtime feedback from projectile position sensors and command-triggered switches in the capacitor bank module. Projectile position and velocity inbore are obtained from a 50 mW, continuous wave, 94 GHz Doppler radar shown in Fig. 4 where the photo insert shows the commercial components (~20 cm long) packaged in the shield housing. The quasi-optical antenna eliminates signal distortion from multimodal power return from the 2.5 cm reflector embedded in the tailboom of the projectile. Precise muzzle velocity control (σ=1% threshold, 0.1% goal) is accomplished by adjusting the position of the armature relative to an energized coil to obtain precise thrust. Tracking and control have been demonstrated at 400 m/s with our 4-stage 50 mm coilgun. High-speed capability of the radar was demonstrated tracking 90 mm projectiles over 2 km/s in the Navy NSWC-Dahlgren 8 m long railgun.

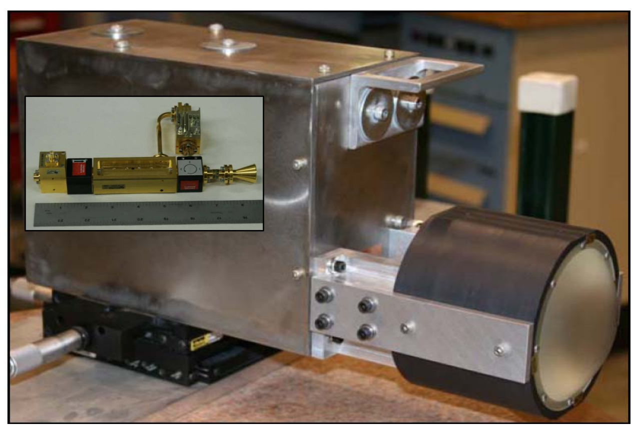

Figure 4. Coilgun projectile tracking radar system.

V. Capacitor Banks

Each coil of the gun is energized by a separate 160 kJ capacitor bank module with its own discharge and crowbar switches and control circuits. Several are shown in Fig. 5 where stripline transmission lines are being prepared for the pulse-discharge connection to the gun. For the laboratory gun, capacitors from previous experiments (circa 1985) are being used. A crowbar circuit with a 250 kA-rated ignitron extends capacitor lifetime and removes coil magnetic energy through resistors. For this laboratory bank system, efforts focused on low-cost components. Designs have yielded cable and stripline transmission lines, spring-steel for crowbar resistors, and minimal machined parts for bank interconnects. Future systems will incorporate magnetic energy recovery without voltage reversal eliminating crowbar components. The compact sparkgap main switch currently used is about the size of future solid-state switches that will fit directly on a single capacitor for each coil. State-of-the-art capacitor technology reduces the present cap volume by a factor of 6, and dielectric films in development will further reduce the volume. [1]

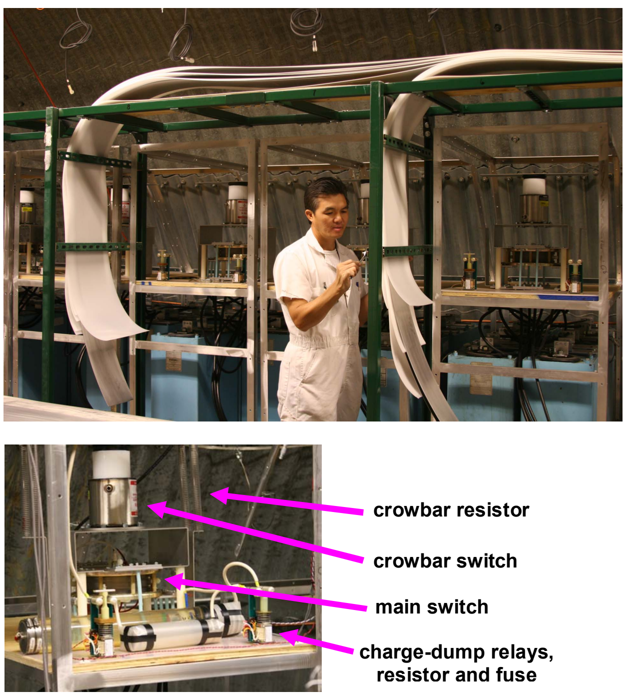

Figure 5. Components of capacitor bank modules.

The stored energy for the laboratory bank modules is larger than would be needed in a gun on a vehicle, since the modules are up to 30 m from the gun due to limited lab space. As all coils in this gun are identical construction, the capacitance and voltage of the capacitor banks are adjusted [8.5 mF at stage 1 (breech) to 0.8 mF at stage 45] such that the current risetime is consistent with the transit time of the armature through a given coil. That capacitance with the required stored energy results in bank voltages ranging from 6 kV at the breech to 20 kV at the muzzle, and the banks deliver current pulses ranging from 65 to 95 kA to the coils.

VI. Barrel Coils

Each coil of the gun is independently fabricated and stacked in an alignment structure to form the barrel. The coil stack will support a fiberglass boretube that guides the projectile as shown in Fig. 6. Each coil has 15 turns forming a 42 μH, 10 mOhm load to its own cap bank module through low-inductance stripline and coax cables. Each of the coils has been pulse-tested in a two-coil fixture with a static projectile at loads representative of gun operation that generate 1 MN thrust equivalent to 1000-atmospheres gas pressure accelerating the round.

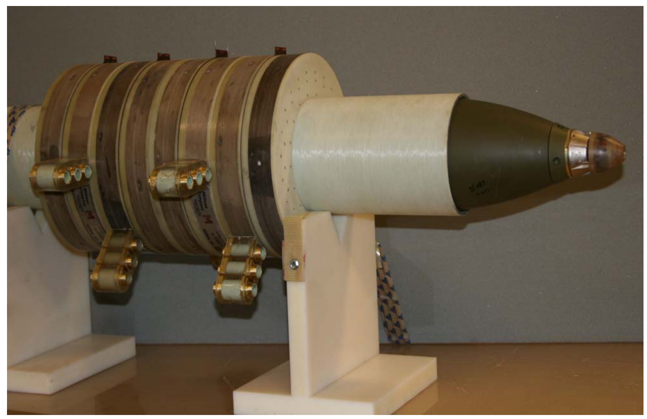

Figure 6. Eight coils surround fiberglass boretube with projectile in mock assembly of barrel without alignment structure.

High mechanical loads are generated in the 25 T coils generating the high thrust which requires significant reinforcement. Hoop-wound PBO-epoxy composite reinforcing shells have been developed to contain the radial forces on each layer of the winding. Dielectric fiber is preferential to carbon due to the latter's electrical conductivity. Figure 7 shows test data of free-standing shells that have the strength and modulus of steel.

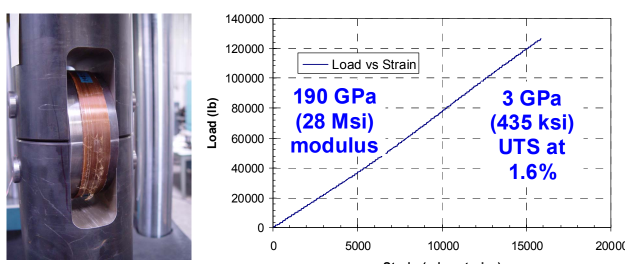

Figure 7. 143 mm ID x 3 mm thick PBO-epoxy composite reinforcing shell in split-D test fixture.

VII. Mount, Baseframe, and Catcher

This hardware will absorb the recoil momentum of the launch of the 18 kg projectile at 420 m/s and is capable of operation up to 500 m/s. The gun mount design is consistent with the FCS NLOS-M mount, but the recoil mechanism has been modified to accommodate the 1 tonne barrel which is lighter than the conventional propellant barrel. Access for two bundles of pulse-discharge cables has been made in that accommodate the 20 cm recoil stroke. The mount is capable of elevating the barrel to high quadrant elevation angles for field test following laboratory demonstrations.

The catcher is a steel box with disposable steel plates capable of stopping 9 MJ rounds. The projectile will fragment in the catcher that slides with high-friction drag on the baseframe linked to the gun mount. This will counter the recoil momentum of the gun barrel.

The shield house is a protective barrier to fragments from the projectile break-up in the catcher. Diagnostic windows will permit photographic documentation of the projectile's integrity in the 2 m drift space between the barrel and catcher.

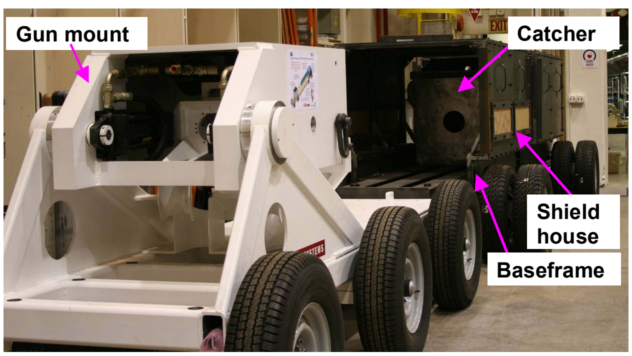

Figure 8. Coilgun mount, baseframe and catcher ready for coil barrel to complete assembly.

VIII. Projected Performance

Simulation of the EM Mortar coilgun performance was conducted with our lumped-parameter circuit code, Slingshot, based on the circuit representation shown in Fig. 2, using detailed geometry of the coil and projectile and bank circuit elements. The code self-consistently solves for currents in coils and the armature through a system of mesh equations with parameters that are position and temperature dependent. Forces are based on mutual inductance gradients, and temperature-dependent resistances are self-consistent with Ohmic heating and material properties. Performance simulation of a 45-stage coilgun is shown in Fig. 9 launching an 18 kg, 120 mm projectile to 424 m/s. The 1.6 MJ muzzle kinetic energy is 22% of the initial stored electrical energy, and the launch time is 14 ms in the 2.1 m acceleration length.

Peak-to-peak variation in the acceleration in the first meter of projectile travel results from using the same coil winding design for all coils and the limited capacitance available from our inventory. Optimized choices of capacitances and coil inductance result in acceleration ripple similar to the 1-2 meter position in Fig. 9. Additionally, the optimum bank-coil combinations improve efficiency to 26% of the initial stored electrical energy. With energy recovery in practical systems, the kinetic energy can be 55% of energy consumed per shot.

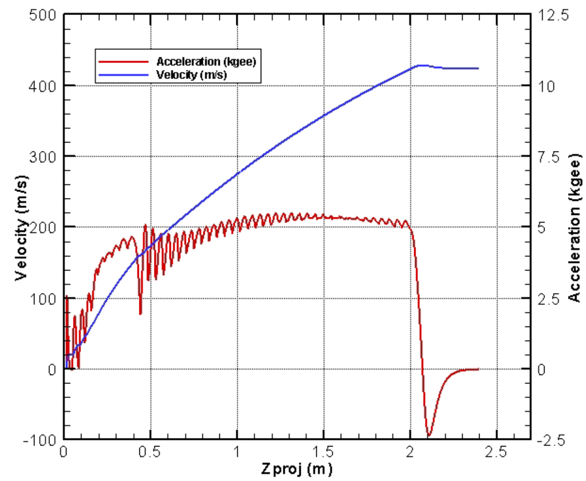

Figure 9. Calculated velocity and acceleration as function of projectile position in 45-stage coilgun.

IX. Assembly Status and Test Schedule

The gun structure and capacitor banks are currently in fabrication, and barrel assembly planned for late summer. Testing with mass-equivalent slugs and XM934 rounds will begin in September 2007.

X. Summary

An EM Mortar coilgun is being developed by DARPA to launch minimally-modified M934 mortar rounds developed by ARDEC for greater muzzle speed and precision than the conventional propellant mortar. Assembly of hardware is near completion, and system testing will commence in Fall 2007.

XI. REFERENCES

[1] F. MacDougall et al., "Large High-Energy-Density Pulse Discharge Capacitor Characterization," presented at 15th IEEE Inter. Pulsed Power Conf., Monterey, Calif., 2005.